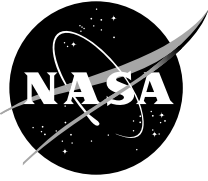


Test and Analysis Capabilities of the Space Environment Effects Team at Marshall Space Flight Center

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TABLE OF CONTENTS

1. INTRODUCTION	1
2. COMBINED ENVIRONMENTAL EFFECTS TEST SYSTEM	2
3. ATOMIC OXYGEN BEAM FACILITY	5
4. ULTRAVIOLET RADIATION TEST CHAMBER	7
5. PLASMA ENVIRONMENT SIMULATION	9
6. MARSHALL MAGNETIC MIRROR	13
7. MICRO LIGHT GAS GUN	14
8. ANALYTICAL CAPABILITIES	15
9. SUMMARY	16
BIBLIOGRAPHY	17

LIST OF FIGURES

1.	Combined environmental effects test system	2
2.	Test chamber graphic with beam lines	3
3.	Reflectance data of silverized Teflon exposed to simulated space environment	4
4.	Low-energy electron test system	4
5.	Atomic Oxygen Beam Facility	5
6.	Z-93P from multienvironment study	6
7.	UV radiation test chamber	7
8.	UV-exposed DC 93-500	8
9.	Space plasma simulator No. 1	9
10.	Typical conductive probe current data from ProSEDS tether investigation	10
11.	Space plasma simulator No. 2, showing anodized sample	11
12.	Anodized aluminum test sample with arc damage	11
13.	Space plasma simulator No. 3	12
14.	Marshall magnetic mirror	13
15.	Micro light gas gun	14

LIST OF ACRONYMS AND SYMBOLS

AO	atomic oxygen
AOBF	Atomic Oxygen Beam Facility
Ar	argon
BPM	beam profile monitor
CEE	combined environmental effects
ESH	equivalent Sun hours
ISS	<i>International Space Station</i>
LEO	low-Earth orbit
M3	Marshall magnetic mirror
MLGG	micro light gas gun
MP&M	Materials, Processes, and Manufacturing (Department)
MSFC	Marshall Space Flight Center
NIST	National Institute of Standards and Technology
NUV	near ultraviolet
PCU	plasma contactor unit
ProSEDS	Propulsive Small Expendable Deployer System
RF	radio frequency
SCARLET	Solar Concentrator Arrays with Refractive Linear Element Technology
SEE	space environmental effects
UV	ultraviolet
VUV	vacuum ultraviolet

TECHNICAL PUBLICATION

TEST AND ANALYSIS CAPABILITIES OF THE SPACE ENVIRONMENT EFFECTS TEAM AT MARSHALL SPACE FLIGHT CENTER

1. INTRODUCTION

The Materials, Processes, and Manufacturing (MP&M) Department at Marshall Space Flight Center (MSFC) is recognized for its contribution to NASA product lines, including space transportation, space science, and flight projects such as the *International Space Station (ISS)*, Chandra X-ray Observatory, and the Next-Generation Space Telescope. The Environmental Effects Group, with its Space Environmental Effects (SEE) Team and Materials Contamination Team, has been an integral part of the MP&M success by the testing, evaluation, and qualification of materials for use on external spacecraft surfaces. The Environmental Effects Group also lends its knowledge and facilities toward the development of advanced space propulsion through the use of electrodynamic tethers and solar sails. This Technical Publication focuses on the capabilities of the SEE Team.

The engineers, physicists, and technicians of the SEE Team evaluate candidate materials by exposing them to laboratory simulations of the space environment, complemented by flight experiments whenever possible. The team's simulation capabilities include charged-particle radiation, ultraviolet (UV) radiation, atomic oxygen (AO), plasma, thermal vacuum, and hypervelocity particle impact. The team operates a unique facility for combined environmental effects (CEE) testing.

2. COMBINED ENVIRONMENTAL EFFECTS TEST SYSTEM

The CEE test system provides the unique capability to irradiate material to a simultaneous or sequential exposure to simulated space environment and perform in vacuo reflectance measurements. The sample size can be up to 7.6 by 7.6 cm (3 by 3 in). To perform in vacuo reflectance measurements, two 2.54-cm- (1-in-) diameter samples are utilized. Exposure can consist of protons, low- and high-energy electrons, near-ultraviolet (NUV) radiation, and vacuum ultraviolet (VUV) radiation, all in a 5×10^{-8} torr vacuum maintained by ion pumps. The CEE test system is shown in figure 1.

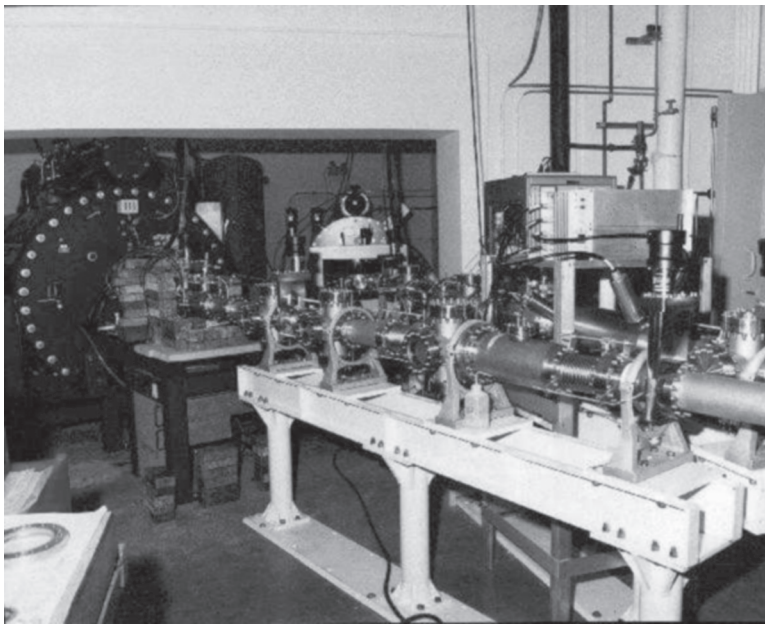


Figure 1. Combined environmental effects test system.

The CEE test system uses two Pelletron® accelerators, an electron accelerator of 200 keV to 2.5 MeV energy, and a proton accelerator of 40 to 800 keV energy. The fluxes for the electron and proton accelerators are 2×10^8 to 3×10^{14} $e^-/\text{cm}^2/\text{s}$ and 2×10^8 to 3×10^{14} $p^+/\text{cm}^2/\text{s}$. An electron flood gun supplies 1–100 keV electrons in addition to the accelerators. Electron flux can be varied from 6×10^9 $e^-/\text{cm}^2/\text{s}$ @ 1 keV to 3×10^{12} $e^-/\text{cm}^2/\text{s}$ @ 100 keV.

A mercury-xenon lamp for NUV radiation is located external to the vacuum test chamber and radiates through a fused silica viewport. The NUV source produces photons over the range of 200 to 2,400 nm, and can produce up to 10 times the Sun's NUV radiation (250 to 400 nm) for accelerated testing. A water filter successfully attenuates the bulk of the infrared portion of the spectrum, and a 90° front surface mirror reflects the NUV into the test chamber. A photodiode is permanently mounted in the test chamber behind the sample position to monitor the NUV intensity. The NUV source is characterized using

a spectral radiometer before each test to determine the relationship between NUV intensity and diode current. A deuterium lamp provides VUV radiation up to 10 times the Sun's UV radiation in the wavelength range of 118 to 200 nm. This VUV source is located in the vacuum chamber and is also monitored by a photodiode.

Each accelerator beam line is equipped with a beam profile monitor (BPM) and Faraday cups. The BPM is a device that measures the intensity distribution and position of a charged beam. The Faraday cup measures the charged-particle beam current. Each accelerator beam line has a Faraday cup that is remotely moved into and out of the charged-particle beam. The CEE test system also has the capability of measuring a sample's total integrated hemispherical reflectance from 250- to 2,500-nm wavelength in vacuum. A temperature-controlled sample holder transports the samples in the horizontal plane from the sample exposure position to the integrating sphere for reflectance measurements. This not only allows monitoring of the samples without breaking vacuum during an exposure but also eliminates any data inaccuracies caused by bleaching when the samples are returned to air. Figure 2 details the sample location in the test chamber, bombardment by the various components of the CEE test system, and in situ measurement capabilities.

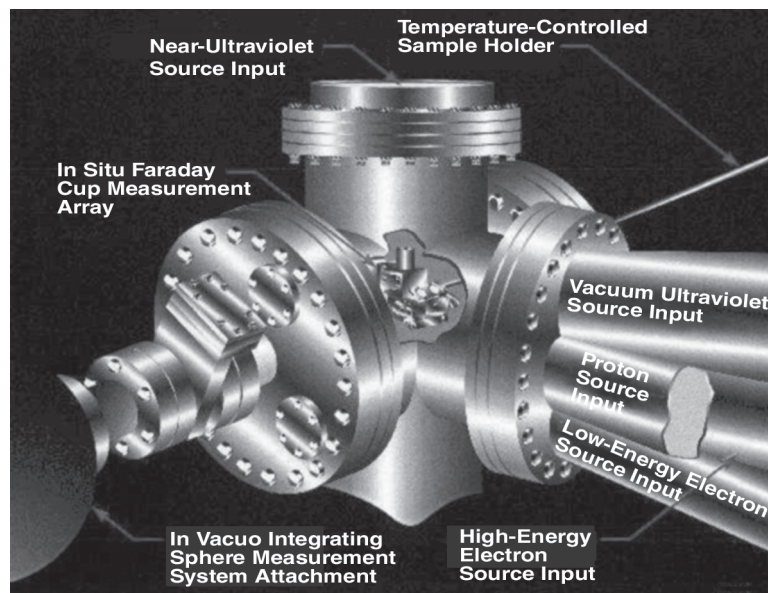


Figure 2. Test chamber graphic with beam lines.

The capability of the CEE test system has been demonstrated on a variety of materials including second surface reflectors, thermal control coatings, and solar sail materials. Proprietary materials are often exposed along with a standard material such as Dupont's silverized Teflon® for comparison. These can also be compared to known flight data as a cross check of simulation accuracy. Figure 3 shows the change in reflectance for silverized FEP Teflon when exposed to electrons, protons, and VUV radiation. The exposure for this sample was $1.93 \times 10^{15} \text{ e}^-/\text{cm}^2$ @ 5 keV, $7.7 \times 10^{14} \text{ e}^-/\text{cm}^2$ @ 12 keV, $1.65 \times 10^{15} \text{ e}^-/\text{cm}^2$ @ 20 keV, $7.7 \times 10^{15} \text{ e}^-/\text{cm}^2$ @ 50 keV, $4.18 \times 10^{15} \text{ p}^+/\text{cm}^2$ @ 40 keV, $1.76 \times 10^{15} \text{ p}^+/\text{cm}^2$ @ 100 keV, $5.5 \times 10^{14} \text{ p}^+/\text{cm}^2$ @ 200 keV, $1.65 \times 10^{14} \text{ p}^+/\text{cm}^2$ @ 300 keV, $6.6 \times 10^{13} \text{ p}^+/\text{cm}^2$ @ 400 keV, $2.53 \times 10^{13} \text{ p}^+/\text{cm}^2$ @ 500 keV, $1.65 \times 10^{13} \text{ p}^+/\text{cm}^2$ @ 700 keV, and 4,416 equivalent Sun hours (ESH) of VUV.

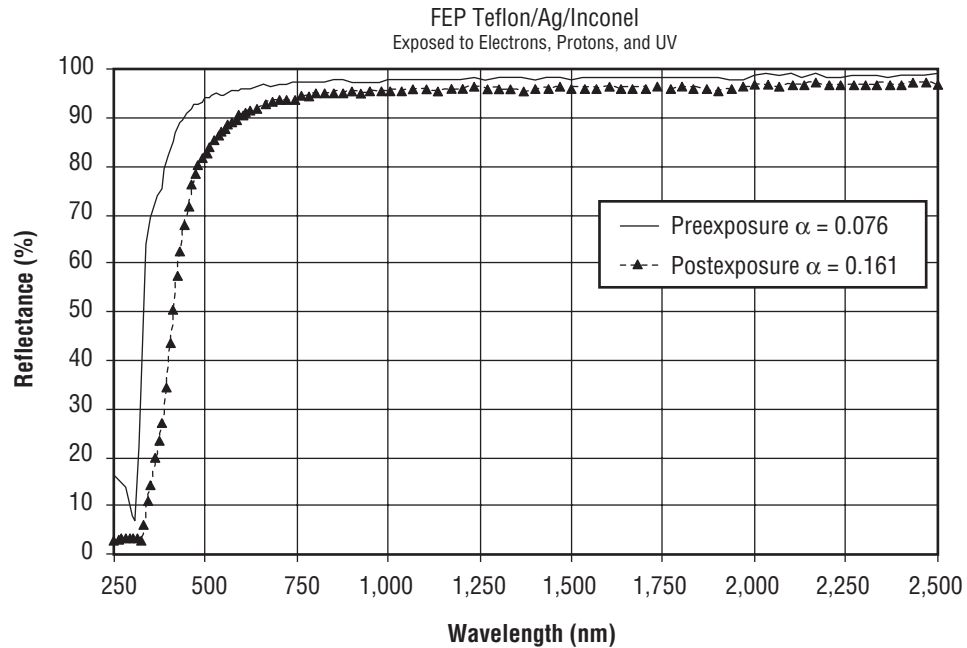


Figure 3. Reflectance data of silverized Teflon exposed to simulated space environment.

A second environment effects facility, the low-energy electron test system combines electrons and UV radiation. An electron gun supplies 1–100 keV electrons to samples up to 20.3 cm (8 in) in diameter. Either NUV or VUV lamps can be added to the exposure. This facility is shown in figure 4.

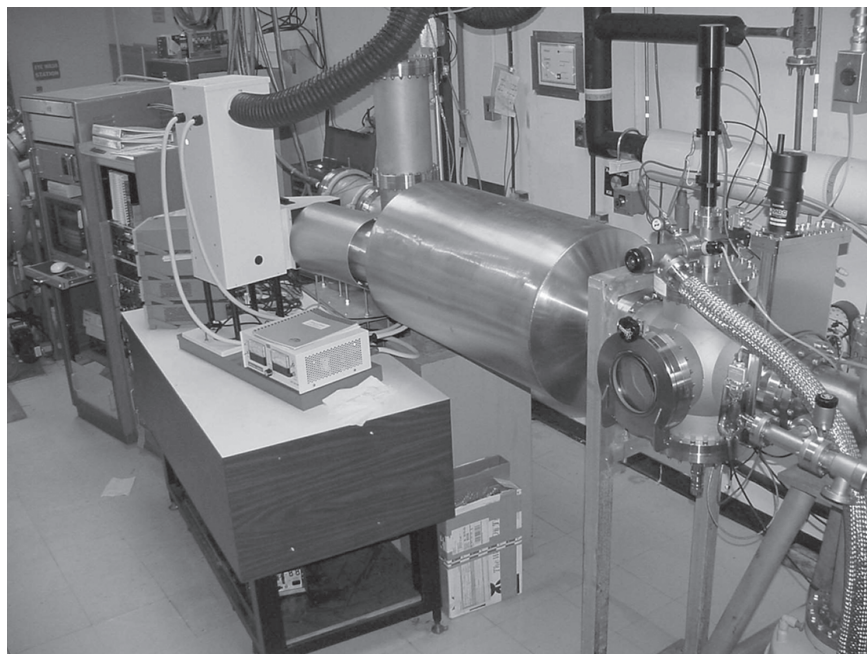


Figure 4. Low-energy electron test system.

3. ATOMIC OXYGEN BEAM FACILITY

The Atomic Oxygen Beam Facility (AOBF) (fig. 5) produces a 5-eV neutral AO beam by placing a metal plate in contact with a magnetically (3–4 kG) confined AO plasma. The AO plasma is produced by a radio frequency- (RF-) driven lower hybrid plasma source. A magnetron supplies 2 kW of power at a frequency of 2.45 GHz to an antenna to produce the plasma. Because of the facility geometry, the AO plasma is magnetically confined such that a 1-cm- (0.39-in-) diameter plasma column is produced on centerline of the test chamber. The plasma column interacts with an electrically biased metallic plate. The bias applied to the plate accelerates ions from the plasma to the plate. During the acceleration process, the ions gain energy equal to the difference in the plasma potential and the neutralizer plate bias. Once the ions hit the plate, they collect an electron from the metal lattice and become neutral. Following collision with the neutralizer plate, the atoms are reflected toward the test specimen at a fraction of their precollision energy. The fraction of energy lost by the reflected atoms is a function of the type of material used to make the neutralizer plate. Because the energy of the reflected atom depends on the plasma potential, which is inherently subject to slight variations, not all atoms will be accelerated by the same potential difference. Thus, the reflected atoms will have a slight energy distribution.

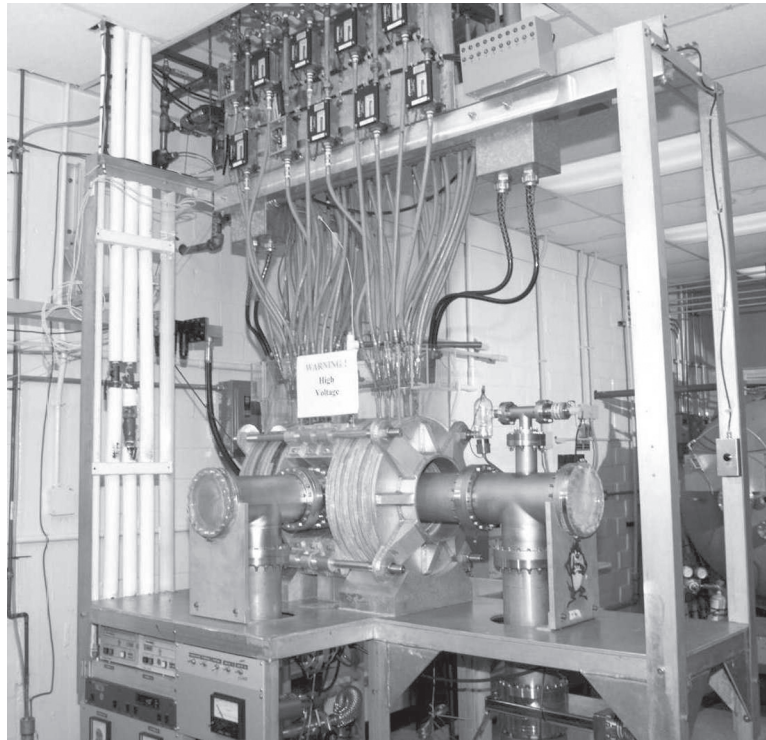


Figure 5. Atomic Oxygen Beam Facility.

The AOBF is capable of supplying 5-eV AO atoms in a pulsed fashion for long periods of time. The limiting factor in the length of a test run is the heating of the RF antenna. During operation of the system, the neutralizer plate collects nearly 4 A of ion current from the plasma. In order to maintain space charge conditions, the same amount of electron current must be lost to the antenna. Heating in the system has been limited by operating in a pulsed fashion with a duty cycle 5–15 percent.

The AO flux produced by the AOBF system is approximately 5×10^{15} atoms/cm²/s. During production of the AO plasma, the system produces electromagnetic radiation during the dissociation and ionization process. Attempts to identify and quantify the radiation using a photodiode with appropriate narrow band filters indicated that the primary radiation line was 130 nm, the AO resonant peak in the VUV region. The VUV intensity was determined to be nearly 200 times the Sun's intensity averaged over the duty cycle.

Sample size for the AOBF is limited to 15.24 cm (6 in) in diameter. Thermocouples monitor the increase in sample temperature due to heat radiating from the neutralizer plate and magnets. Sample temperature ranges from 50 to 60 °C (122 to 140 °F), depending on the duty cycle.

Atomic oxygen erodes many polymeric materials and has been shown to bleach ceramic coatings such as Z-93P, which is zinc oxide pigment in a potassium silicate binder. A recent study looked at the effects of contamination, UV radiation, and AO exposure on the optical properties of various spacecraft materials such as Z-93P. When the contamination is a hydrocarbon, it is removed by AO erosion, and the solar absorptance improves (fig. 6). When the contamination is silicone, a silicate layer can be formed.

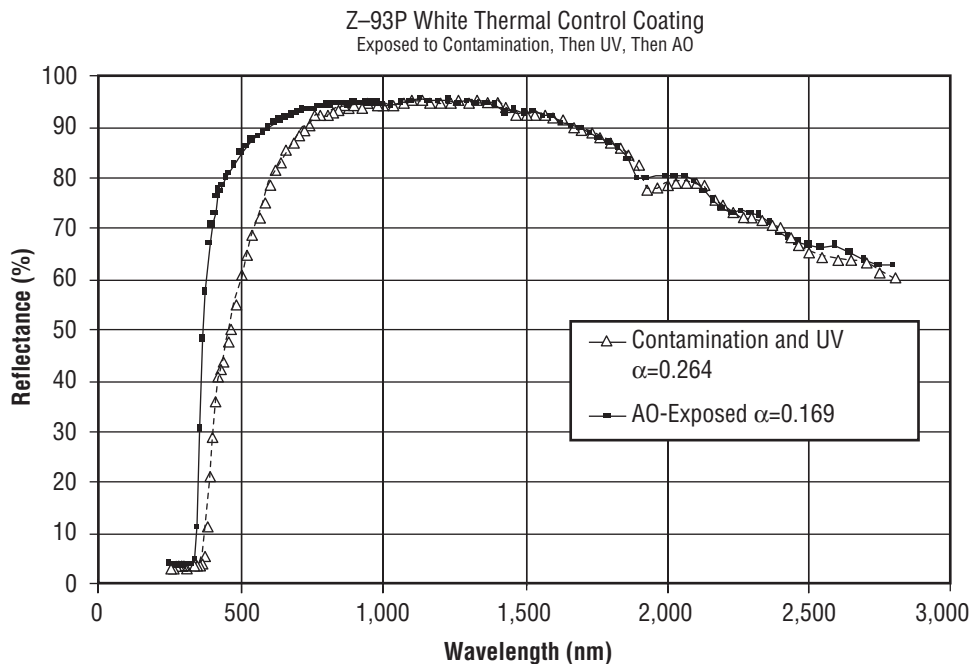


Figure 6. Z-93P from multienvironment study.

4. ULTRAVIOLET RADIATION TEST CHAMBER

For solar UV radiation effects studies, the SEE Team has three test systems. Two of the test systems can expose samples to both NUV and VUV radiation. The sample area is 15.2 cm (6 in) in diameter and usually holds nineteen 2.54-cm- (1-in-) diameter samples. One test system (fig. 7) has the added capability of sample temperature control to allow the exposure of samples up to 180 °C (356 °F). The third UV simulator is limited to NUV radiation only and can irradiate up to nine 2.54-cm- (1 in-) diameter samples.

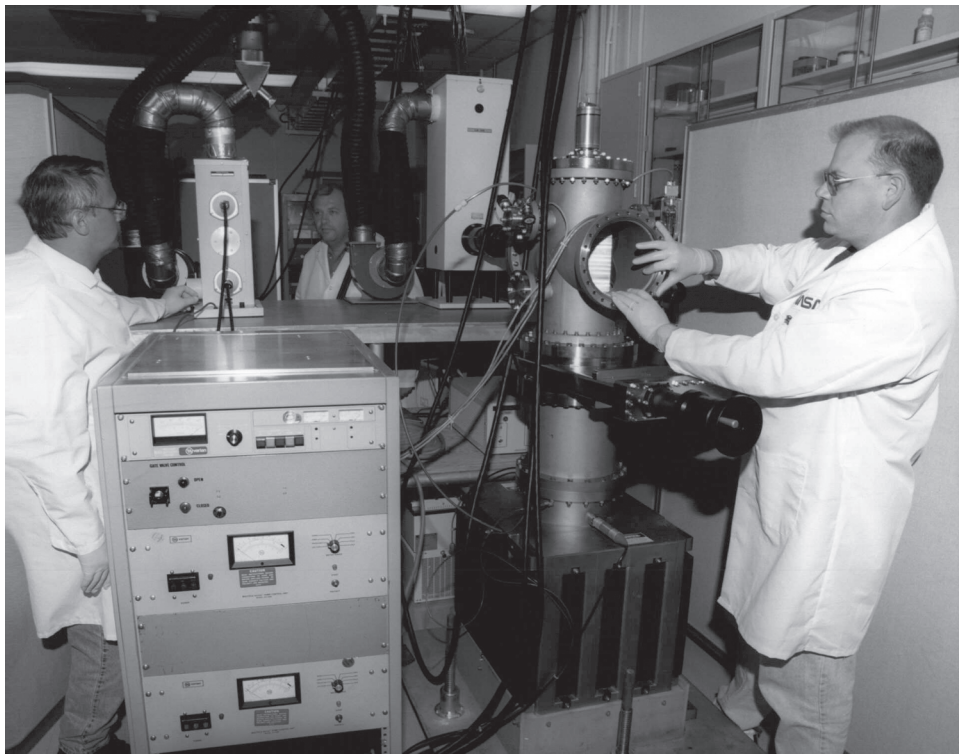


Figure 7. UV radiation test chamber.

Solar intensity for NUV radiation as delivered by a mercury-xenon lamp can be up to 10 equivalent Suns, but samples are generally exposed to 2–3 equivalent UV Sun levels to minimize thermal effects. VUV radiation, electromagnetic radiation produced in the 110- to 200-nm wavelength range, is produced by either a 25 or 150 W deuterium lamp. This provides up to 600 times the equivalent solar VUV, depending on the wavelength selected, without significant sample heating. Deuterium sources produce 80 times solar flux irradiance at Lyman alpha (121.6 nm). A NIST-calibrated photodiode is used to calibrate spectroradiometric measurements through the VUV range.

Contamination-free operation is achieved by utilizing cryogenic absorption pumps and ion pumps to achieve 10^{-7} torr vacuum or better. The systems are protected against temporary power loss. Thermal control coatings have been exposed to simulated solar UV radiation at MSFC for up to 9 equivalent years in low-Earth orbit (LEO). Usually, samples are exposed for a few hundred ESH as a screening test, then for longer UV doses as the customer requires. For example, several candidate films were tested at MSFC for the SCARLET-II array on NASA's Deep Space 1 spacecraft. The films are formed as Fresnel lenses to concentrate solar energy onto high-efficiency solar cells, decreasing the area of solar cells needed for power. These thin polymer films must maintain good optical transmission and mechanical integrity. The film samples were exposed to NUV and VUV for 7,772 ESH. Transmission changes are shown in figure 8.

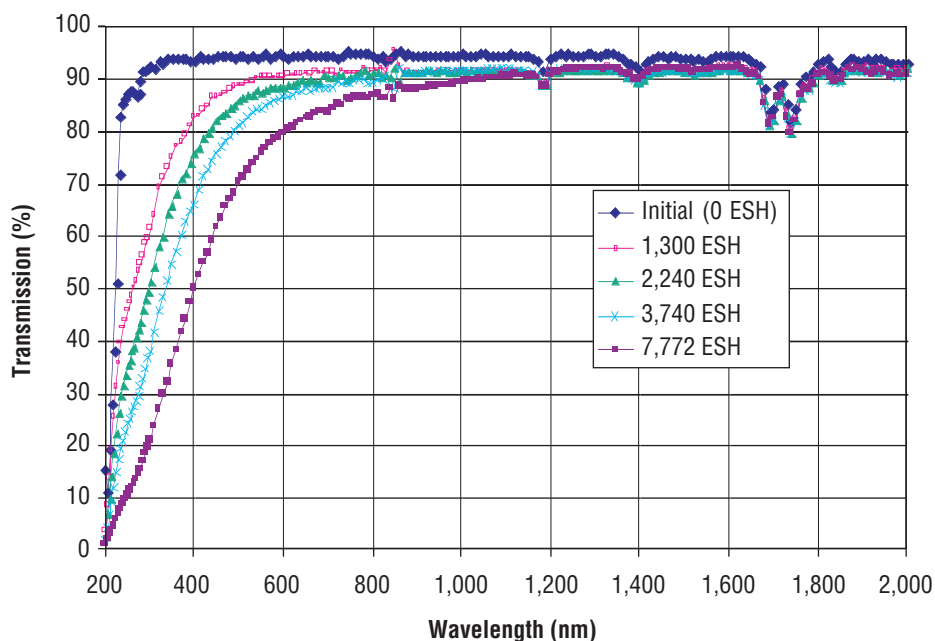


Figure 8. UV-exposed DC 93-500.

5. PLASMA ENVIRONMENT SIMULATION

The SEE Team has three plasma simulators for studying current collection, arcing, electrical conductivity and spacecraft charging issues. Space plasma simulator No. 1 (fig. 9) is a 1.2-m-diameter by 2.5-m-long (4- by 8.3-ft) cryopumped vacuum chamber capable of a base pressure in the low 10^{-7} torr range. Plasma is produced in the chamber using a hollow cathode plasma source because it produces a fairly uniform low-density ($10^6/\text{cm}^3$), low-temperature (1 eV) plasma that is a close simulation of the LEO environment. It can be operated with various gas species including argon (Ar), xenon, oxygen, helium, and hydrogen, though Ar is typically used. Because the chamber is used to study mechanisms for charge collection, Ar ions are a good first-order approximation. The chamber also contains both Langmuir and emissive probes and retarding field potential energy analyzers to measure the plasma properties in the chamber.

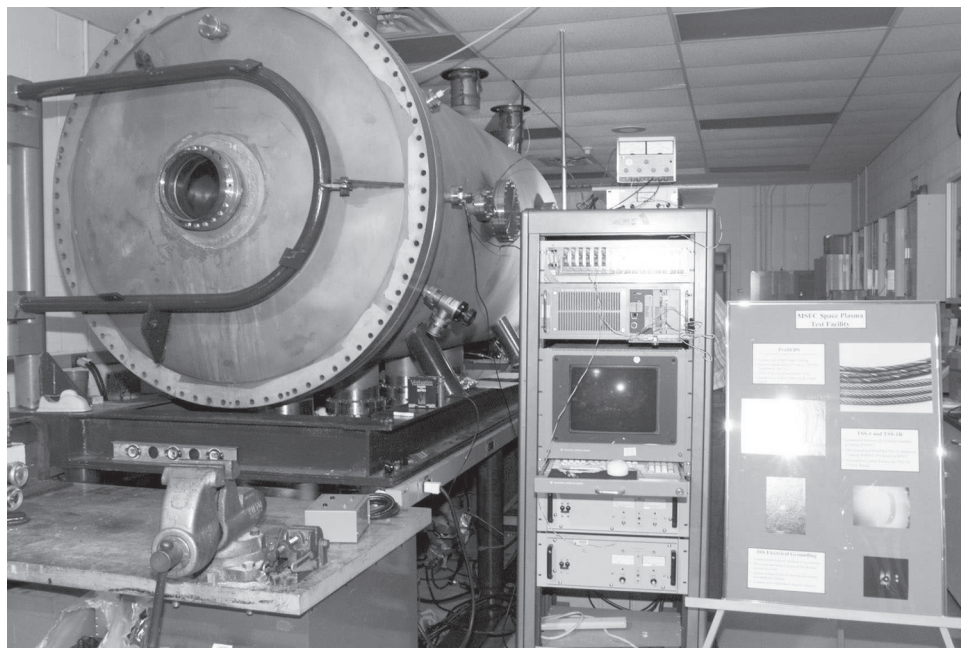


Figure 9. Space plasma simulator No. 1.

Space plasma simulator No. 1 was used extensively in testing materials and components for the Propulsive Small Expendable Deployer System (ProSEDS) flight experiment. ProSEDS is an on-orbit demonstration of the electrodynamic propulsion capabilities of tethers in space. The SEE Team tested conductive and insulative tether materials for electrical properties in vacuum (fig. 10). Life-cycle testing of the ProSEDS hollow cathode plasma contactor was also carried out in this test chamber.

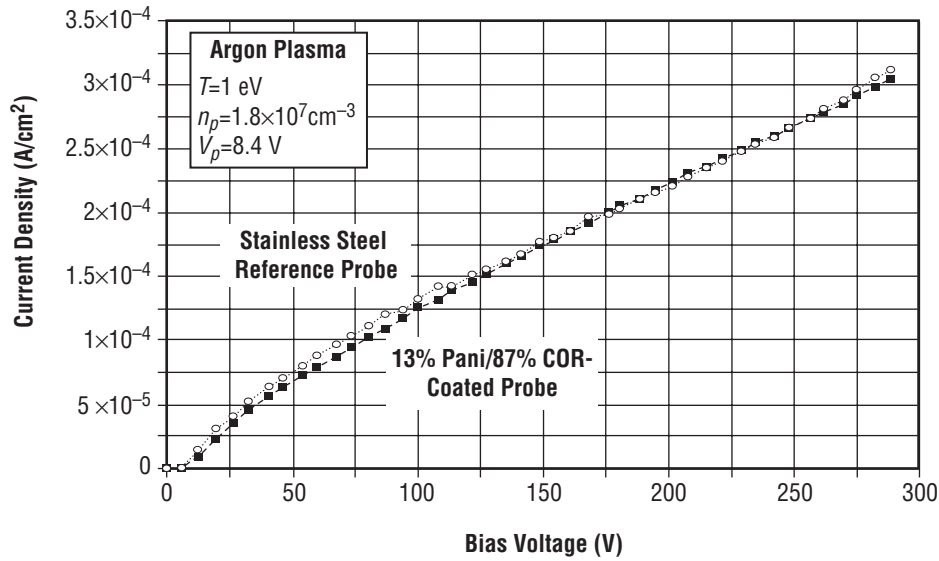


Figure 10. Typical conductive probe current data from ProSEDS tether investigation.

Space plasma simulator No. 2 (fig. 11) is a 0.91-m-diameter by 1.22-m-long (3- by 4-ft) vacuum chamber capable of a base pressure in the low 10^{-7} torr range. It is similar to space plasma simulator No. 1 in the production of plasma. Probes are used to verify the electron temperature, T_e , in the range of 0.95 to 1.6 eV and plasma density, n_e , in the range of 0.76 to $1.3 \times 10^7/\text{cm}^3$. Space plasma simulator No. 2 was used most recently for testing in support of the *ISS* plasma contactor unit (PCU). The role of the PCU is to maintain the potential of the *ISS* within 40 V of the ambient plasma potential. In the event of a PCU failure, the *ISS* structure may charge to -160 V with respect to the LEO plasma because of the use of high-voltage photovoltaic solar arrays. Breakdown voltage and arc damage were evaluated for the anodized aluminum used in the meteoroid/debris shields (fig. 12) and extravehicular mobility unit hardware.

Space plasma simulator No. 3 (fig. 13) is a 1.2-m-diameter by 1.5-m-long (4- by 5-ft) vacuum chamber and also produces an Ar plasma. Electron temperature is in the 0.8 to 1 eV range, and plasma density is $10^6/\text{cm}^3$. Space plasma simulator No. 3 has been used most recently for high-voltage solar array testing with voltages up to 300 V.

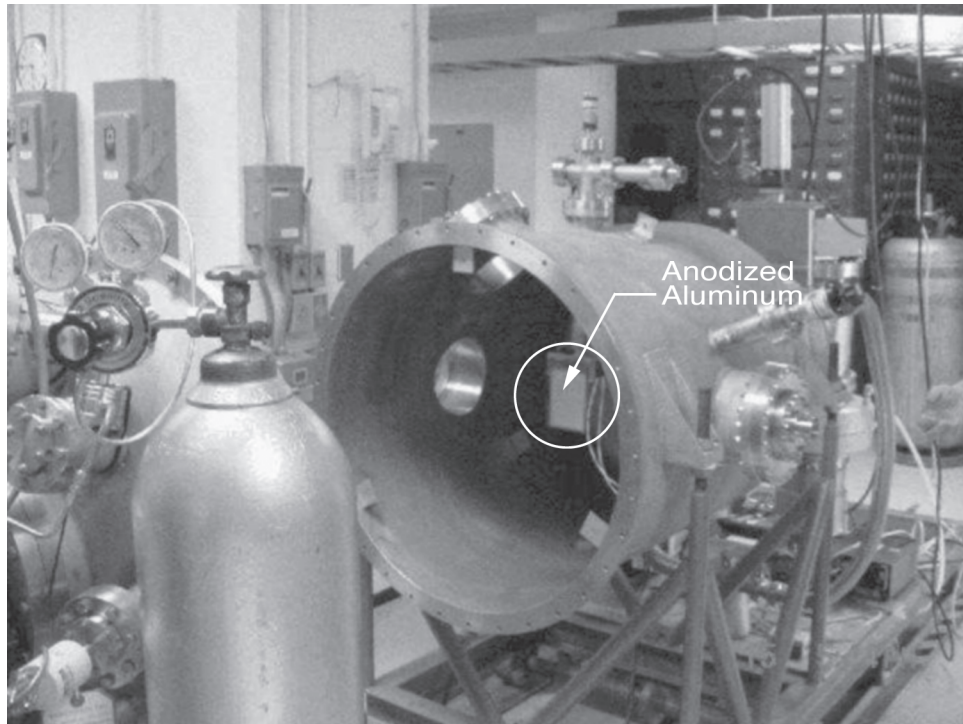


Figure 11. Space plasma simulator No. 2, showing anodized sample.

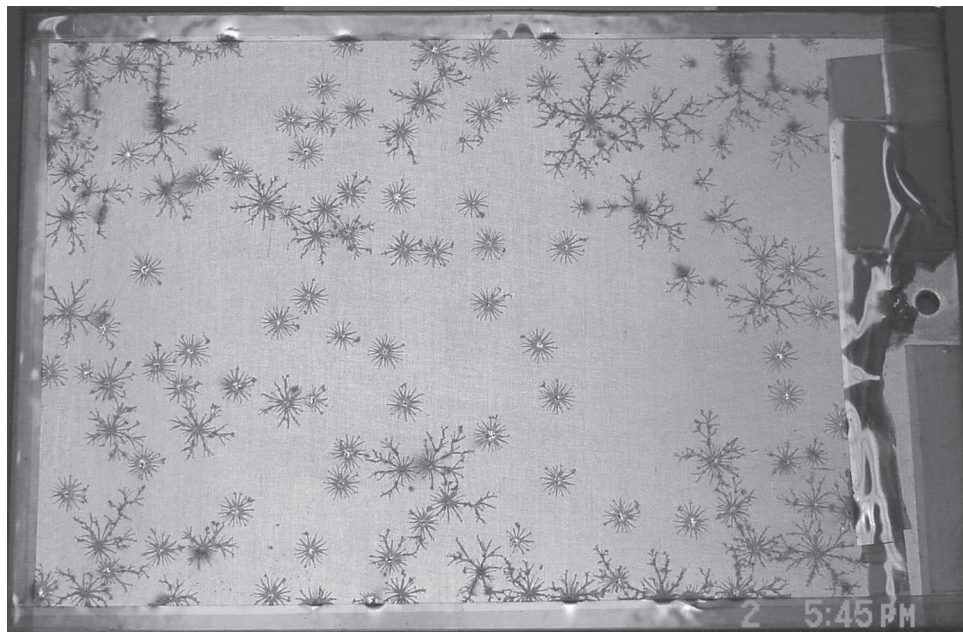


Figure 12. Anodized aluminum test sample with arc damage.

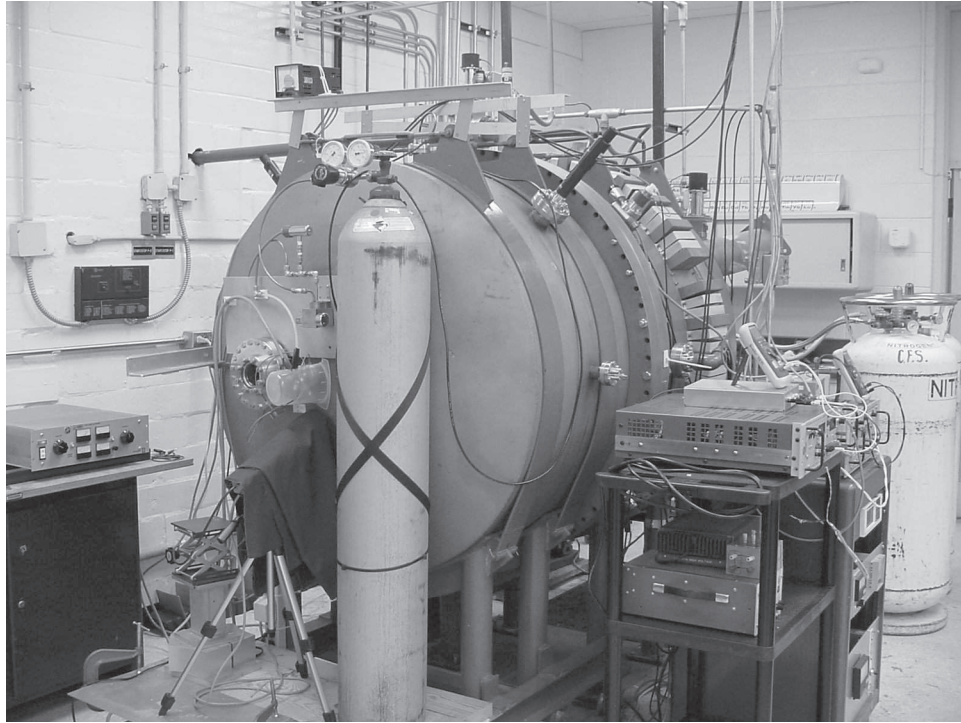


Figure 13. Space plasma simulator No. 3.

6. MARSHALL MAGNETIC MIRROR

The Marshall magnetic mirror (M3), shown in figure 14, was built to study advanced space propulsion techniques using a magnetically confined plasma. Magnetic fields of ≈ 1 kG are used to contain the plasma. Plasma propulsion is expected to yield a high specific impulse. By adding an electron beam, it may be possible to increase the plasma density and temperature, thereby increasing the thrust generated for propulsion. At time of publication, the peak plasma density is $10^{10}/\text{cm}^3$ with an electron temperature of 10 eV. Studies are continuing for optimizing the power coupling between the electron beam and the plasma by varying the neutral gas type and density, magnetic field strength and configuration, microwave power input to the plasma, and the electron beam energy and current.

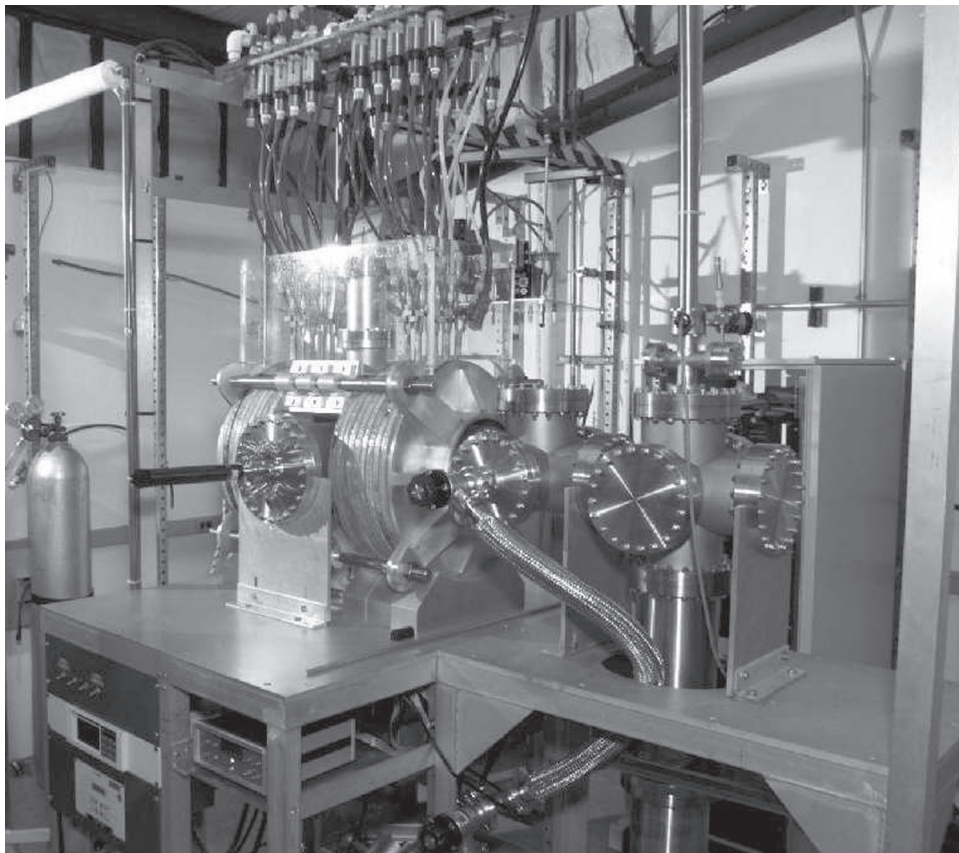


Figure 14. Marshall magnetic mirror.

7. MICRO LIGHT GAS GUN

Meteoroid and orbital debris impacts are a serious concern for spacecraft in orbit. More than 9,000 objects are being tracked (at publication time), with millions more particles too small for radar or telescopes to track. These particles travel at hypervelocity speeds, with an average velocity of 10 km/s for orbital debris and up to 60 km/s for micrometeoroids. Micrometeoroids and space debris can puncture manned spacecraft, pit windows and telescope mirrors, and damage solar arrays and thermal radiators. In order to avoid collisions with space debris, spacecraft may be forced to use limited fuel supplies.

To quantify the damage caused by debris particles or qualify debris protection systems, MSFC has the micro light gas gun (MLGG). The MLGG is capable of accelerating small particles (0.1–1 mm in diameter) to velocities of 3–9 km/s. The test chamber allows for target samples up to 20 by 20 cm. Projectile velocity is measured with each test using photodiodes attached to an oscilloscope.

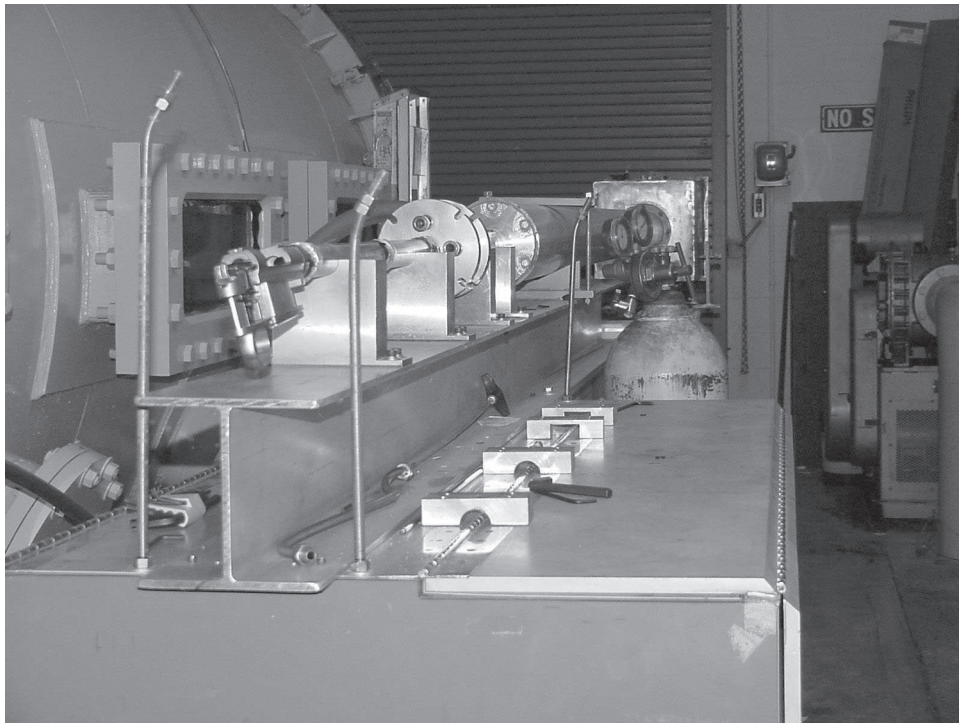


Figure 15. Micro light gas gun.

8. ANALYTICAL CAPABILITIES

A variety of instruments are used for pretest and posttest characterization. Microgram mass changes of samples can be measured. Solar absorptance is measured for the wavelength range of 250 to 2,800 nm using an AZ Technology laboratory portable spectrophotometer. Reflectivity and transmission measurements can be made using a PerkinElmer Lambda 19 spectrophotometer for 185 to 2,500 nm. Infrared reflectance measurements are made using an AZ Technology TEMP 2000 infrared reflectometer or an AZ Technology laboratory portable infrared reflectometer for spectral measurements between 2.5 and 20 μ wavelengths. Reflectance or transmission measurements in VUV wavelengths of 120–300 nm can be made with a McPherson 0.5-m scanning monochromator with a deuterium lamp. The bidirectional reflectance distribution function can be measured using a TMA Quickscan with detectors for measuring reflectance at 632.8 nm at up to 10 different angles.

Microscopes, including stereo, light-section, and scanning electron microscopes, are routinely used in evaluating changes in surface morphology. Thickness loss can be determined using a Veeco Instruments' Dektak[®] profilometer or a Wyko[®] angstrometer.

The Materials Contamination Team of the Environmental Effects Group also has many capabilities for materials characterization. Ellipsometry can be performed on samples to determine changes in coating thickness, and Fourier transform infrared analysis is available for identifying chemical changes. The Contamination Team also studies materials outgassing and maintains a database of material thermal vacuum stability and compatibility with sensitive optics. Thermal properties can be determined using a differential scanning calorimeter.

9. SUMMARY

The world-class facilities of the Environmental Effects Group at MSFC provide valuable information to designers, engineers, and scientists on the behavior of materials in the space environment. Each system fulfills a need for materials testing in order to qualify them for use on spacecraft. These test facilities have also been used in postflight analysis of experiments from the Long-Duration Exposure Facility, the passive optical sample assembly, the space portable spectrophotometer, and the optical properties monitor. Atomic oxygen, UV radiation, charged particles, plasma, and thermal vacuum may affect the optical, mechanical, and electrical properties of materials. The synergistic effects of these aspects of the space environment are still not completely understood and continue to be investigated. Data from these specialized test systems, combined with analytical results from material flight experiments, enable the SEE Team to determine optimum materials for use on spacecraft.

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13. ABSTRACT (Maximum 200 words) Marshall Space Flight Center has developed world-class space environmental effects testing facilities to simulate the space environment. The combined environmental effects test system exposes temperature-controlled samples to simultaneous protons, high- and low-energy electrons, vacuum ultraviolet (VUV) radiation, and near-ultraviolet (NUV) radiation. Separate chambers for studying the effects of NUV and VUV at elevated temperatures are also available. The Atomic Oxygen Beam Facility exposes samples to atomic oxygen of 5 eV energy to simulate low-Earth orbit (LEO). The LEO space plasma simulators are used to study current collection to biased spacecraft surfaces, arcing from insulators and electrical conductivity of materials. Plasma propulsion techniques are analyzed using the Marshall magnetic mirror system. The micro light gas gun simulates micrometeoroid and space debris impacts. Candidate materials and hardware for spacecraft can be evaluated for durability in the space environment with a variety of analytical techniques. Mass, solar absorptance, infrared emittance, transmission, reflectance, bidirectional reflectance distribution function, and surface morphology characterization can be performed. The data from the space environmental effects testing facilities, combined with analytical results from flight experiments, enable the Environmental Effects Group to determine optimum materials for use on spacecraft.				
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